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Preliminary Measurements of Partial Discharge Inception Voltage Degradation With Constant Temperature Aging of Magnet Wire Twisted Pairs for Electric Aircraft Motors

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Abstract

Electric aircraft require high reliability electric motors to meet the stringent safety standards of the aviation industry. Motor winding insulation lifetime and reliability models for electric aircraft applications are needed to enable design of high reliability and high-performance electric motors for aviation applications. Three primary stresses effect the lifetime of motor winding insulation: thermo-chemical, mechanical, and electrical. This paper presents preliminary experiments on twisted pairs of magnet wire targeting understanding the thermo-chemical degradation of motor winding insulation through constant temperature thermal aging. Three types of magnet wire twisted pairs where tested: polyimide insulated magnet wire, epoxy coated polyimide insulated magnet wire, and epoxy potted polyimide magnet wire. The degradation of the samples over time at temperature was tracked using partial discharge inception voltage measurements. These initial experiments were used for development of procedures and expertise in partial discharge testing and thermo-chemical aging to inform future testing. The preliminary nature of these experiments should be noted when viewing the results. Lessons learned from the experiments are documented.

1.0 Introduction

To achieve public acceptance, electric and hybrid electric aircraft must achieve safety and reliability levels on par with today's aircraft. Electric motors are a key component in the drivetrains of electric and hybrid electric aircraft and correspondingly the reliability of those vehicles is highly dependent on the reliability of the electric motors (Ref. 1). One of the dominant causes of motor failure is insulation degradation and short circuits in the motor windings. Motor winding insulation design, testing, modeling, and qualification process are not presently developed with sufficient detail for the design of high reliability motors for electric aircraft applications (Ref. 2).

Motor winding insulation lifetimes are driven by three primary stresses: thermal-chemical, mechanical, and electrical stress (Ref. 3). This paper presents preliminary testing targeted toward understanding thermo-chemical aging of magnet wire insulation relevant to electric aircraft applications. The current commonly used rating system for the thermo-chemical lifetime of motor winding insulation is thermal classes (Ref. 3). Thermal classes of magnet wire per NEMA 1000 (Ref. 4) are based on the ASTM D2307 testing standard (Ref. 5). The thermal classification provides an estimate for the temperature at which the insulation is expected to have 20,000 h of life in an air environment (Ref. 3).

While these thermal classes are used as thermal limits for machines in most designs, they are not necessarily sufficient for the design of a high reliability aerospace motor for four primary reasons (Ref. 2):

1. The 20,000 h lifetime is extrapolated from accelerated aging at other temperatures based on Arrhenius's law (Ref. 3). The 20,000 h life estimate relies on comparison of the accelerated aging data of an insulation system to the accelerated aging data of a reference insulation system which has a known lifetime in a similar application. For electric aircraft propulsion motors, reference insulation systems with known lifetime in the application do not exist.
2. 20,000 h is an estimate of the mean lifetime of the insulation system. No information is contained in the estimate for the probabilistic distribution of the insulation systems lifetime around the mean value. Correspondingly the temperature class cannot be used to design a high reliability machine for a given lifetime.
3. Failure when completing insulation testing per ASTM D2307 (Ref. 5) is based on electrical break down of the insulation at a voltage corresponding to an electrical field of approximately 12 kV/mm. No information is contained in the rating for the thermochemical aging lifetime of the insulation to breakdown at different electrical field levels. Additionally, for inverter-fed Type 1 insulated magnet wires, the likely insulation type for electric aircraft motors, the onset of repetitive partial discharge can be considered the end of life for the insulator (Refs. 3 and 6). As a result, partial discharge inception not breakdown of the insulation is the more relevant failure criteria to measure when aging magnet wires for electric aircraft applications.
4. The estimated lifetimes are only relevant to an ambient air environment which depending on the motor design and mission may not be a relevant environment for a given aerospace motor.

Recent work by Rumi et al. (Refs. 7 and 8) presented results for the change in partial discharge inception voltage (PDIV) for magnet wire twisted pairs after aging at constant temperature. Both unimpregnated and impregnated wires were tested. The exact geometry of the impregnated specimens in the testing is unclear. Loubeau et al. (Ref. 9), measured the change in PDIV of impregnated motorrettes with both constant temperature and thermal cycling. The full motorette specimens however are likely to have significant mechanical stresses in their insulation systems even when aged at constant temperature.

This paper presents results of a preliminary testing campaign targeted at tracking changes in motor winding insulation PDIV with aging at constant temperature. Three types of twisted pairs where used: polyimide-insulated magnet wire, epoxy-coated polyimide-insulated magnet wire, and epoxy-potted polyimide-coated magnet wire. This preliminary set of tests were used to work through issues and learn lessons about how to conduct this kind of aging on magnet wire. The following sections discuss the experimental setup (Section 2.0), the testing results (Section 3.0), and conclusions (Section 4.0).

2.0 Experimental Setup

2.1 Specimens

Four different twisted pair specimen sets were produced and tested. The four sample sets were

- Unimpregnated insulated magnet wire
- Magnet wire potted in epoxy #1
- Magnet wire potted in epoxy #2
- Magnet wire coated in epoxy #2

TABLE I.—DATA SHEET PROPERTIES FOR THE TWO EPOXIES USED

	Thermal conductivity	Dielectric constant	Dielectric strength, kV/mm	CTE, ppm/°C	Glass transition temperature, °C	Thermal class, °C	Max use temperature, °C
Epoxy #1	0.26	3.5	21.6	101×10^{-6}	~140	~	315
Epoxy #2	1.9	~	18.5	14.9×10^{-6}	204	180	~

All twisted pairs were constructed with heavy build 16 AWG NEMA 1000 MW-16C magnet wire (Ref. 4). The twisted pairs were constructed per (Ref. 5). The datasheet properties for the two epoxies relevant to the testing completed here are provided in Table I as a reference. The authors have not independently verified the property values. The first epoxy (Ref. 10) is the unfilled epoxy used in NASA's High Efficiency Megawatt Motor (HEMM) (Refs. 11 to 14) and in the thermal cycling testing completed in Reference 15. It should be noted that the datasheet values for this epoxy's coefficient of thermal expansion (CTE) and thermal conductivity changed since its selection for HEMM and the publication of References 11 to 14. The epoxy has no known thermal class but a high max use temperature. The second epoxy (Ref. 16) is common motor potting epoxy that uses ceramic fillers to obtain a high thermal conductivity. It has an advertised thermal class of 180 °C and a much lower CTE than epoxy #1.

Examples specimens of each type prior to aging are shown in Figure 1. Both the coated and unimpregnated twisted pairs were held in a specimen holder per (Ref. 5). A ceramic material was used for the end plates of the holder that are in contact with the specimens to enable high temperature capability while avoiding PD between the specimens and the end plates. The potted specimens were incased in plates of epoxy. No holder was used for these specimens.

For the specimens potted in epoxy #1, the potting process for HEMM was replicated (Ref. 11). The specimens were vacuum pressure impregnated (VPI) in a commercial VPI chamber. A vacuum level of less than 2 torr was achieved during outgassing. A pressure level of 80 psi was used to compress the epoxy after outgassing. The specimens were cured in their molds at 121 and 176 °C. They were then removed from their molds before a final cure at 232 °C.

For potting with epoxy #2, both parts of the 2-part epoxy were separately heated to ~60 °C and mixed individual before combining and mixing. The mixed epoxy was then outgassed in a vacuum oven at 60 °C for 26 min to a pressure of 90 torr. The epoxy was then poured into a mold containing the twisted pair specimens to be potted. Some of the epoxy was brushed onto the other twisted pairs to create the coated specimens. The specimens were then degassed at an 80 °C temperature in the same vacuum oven for 31 min. The specimens were cured at 110 °C with the potted specimens still in their molds. The potted specimens were then removed from their mold and 2 h curing cycles were completed at 120, 150, 180, and 210 °C for all the specimens as specified in the manufacturer datasheet.

2.2 Partial Discharge Experimental Setup

Partial discharge inception voltage was measured on each specimen before testing and after every thermal aging cycle. Figure 2 shows the partial discharge (PD) testing setup. Two methods of detecting PD were implemented. The one for which results are reported in this paper is a commercial partial discharge detecting system developed per IEC 60270 (Ref. 17). PD is detected in a coupling circuit in parallel to the test object. The coupling circuit consists of a coupling capacitor and a measurement impedance. The coupling capacitor in the system is 1.3 nF. Voltage is measured across the measurement

impedance and processed by the commercial measurement instrument to quantify both applied voltage to the test article and the magnitude of PD pulses in pC. Calibration of the PD measurement was completed before every test with an IEC 6027 calibration unit.

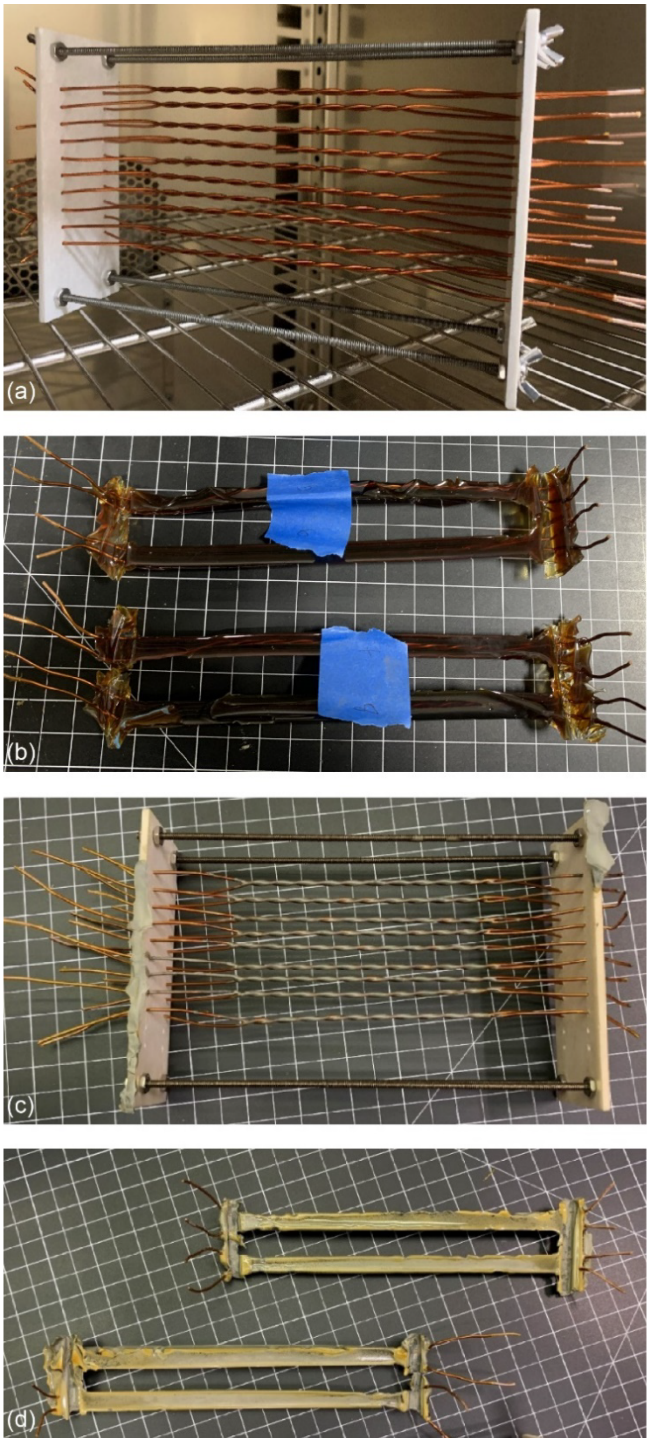

Figure 1.—Example specimens of each type prior to aging. (a) Example unaged unimpregnated insulated magnet wire twisted pairs. (b) Example unaged epoxy #1 potted twisted pairs. (c) Unaged epoxy #2 coated twisted pairs. (d) Unaged epoxy #2 potted twisted pairs.

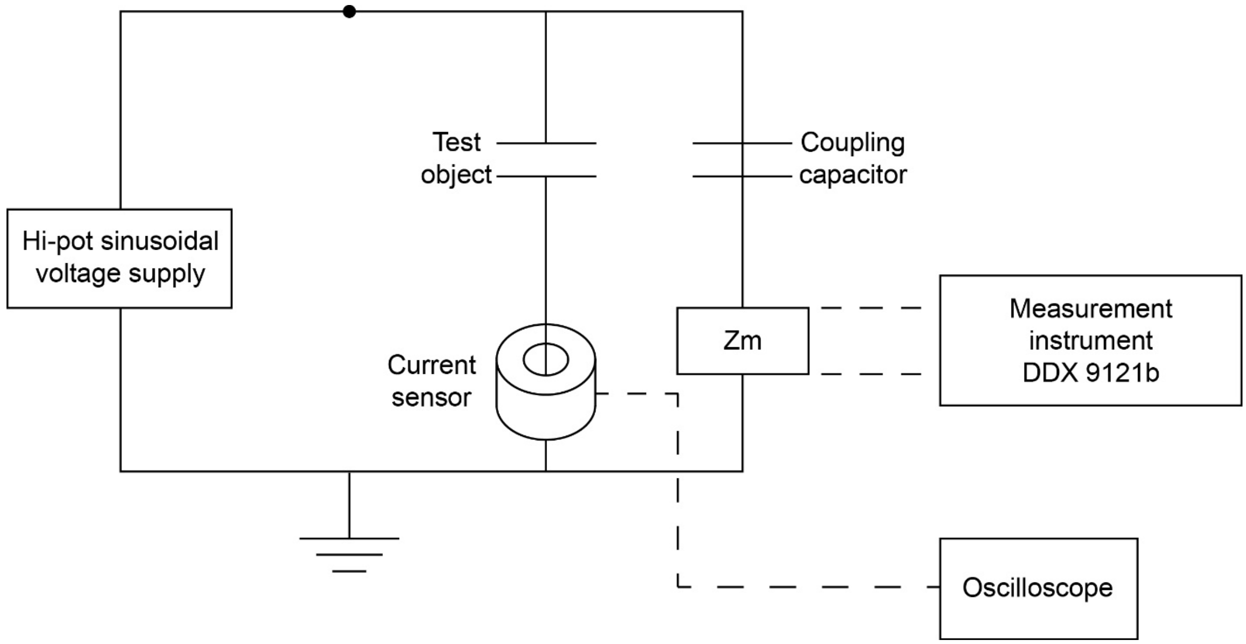

Figure 2.—Schematic of partial discharge testing setup.

TABLE II.—VOLTAGE LEVELS USED IN
PDIV MEASUREMENT TESTING

Voltage Levels in Vrms					
450	500	550	600	650	675
700	725	750	775	800	825
850	875	900	925	950	975
1000	1050	1100	1150	1250	1300
1350	1450	1500	1600	1700	1800
1900	2000	2100	2200	2300	2400

The secondary PD detection system consists of a high frequency current transformer, with bandwidth of 1200 Hz to 500 MHz, on the ground side of the test object and an oscilloscope. In the work reported here this sensor was only used as a secondary validation for PD detected by the primary detection system in some tests. No direct results are reported from this system in this paper, but it is included in the test setup description for completeness.

Voltage was supplied to the test setup at 60 Hz using a commercial hi-pot tester. As discussed in Reference 2 and shown in References 7 and 8, converter frequencies will affect the PDIV measurement and more relevant results to converter fed motor applications can be obtained if PDIV is measured with converter frequencies. A 60 Hz voltage supply is used in the work presented here as a starting point to collect initial degradation data while a test apparatus capable of generating converter voltage waveforms is being developed. Sinusoidal voltage was supplied to the setup at incremental levels for 5 s at a time. Rise and fall time for the voltage was 1 s. The levels used are listed in Table II. Voltage levels were selected based on earlier testing of twisted pairs. Based on the results of the testing here, the voltage levels used will be refined for subsequent testing campaigns.

Calibration was carried out with a 20 pC signal from the calibration unit before each round of PDIV testing. Calibration was carried out with the voltage supply powered off. The noise floor for the testing with the high voltage supply turned on measured in the range of 48 pC in this initial round of testing. The PDIV of an unaged reference twisted pair was measured before every round of testing. Appendix A provides the noise and calibration information collected before each round of testing.

Specimen leads were mechanically cleaned to remove a portion of the insulation layer before the first test and then to remove the copper oxidation layer developed in thermal aging before every PDIV measurement. This manual insulation and oxidation removal was at first done using sandpaper before a mechanized insulation removal system was obtained. Specimen lead cleanliness often led to poor electrical connections and anomalous PDIV readings when cleaning was completed with sandpaper. Resanding often led to more consistent PDIV measurements. Use of the mechanized insulation removal system reduced the variability in lead cleanliness. The inconsistency of cleaning completed with sandpaper and the mechanical vibration applied to the specimens both with the sandpaper and mechanized insulation remover should be noted when viewing the results in Section 3.0.

PDIV in this paper was determined when a PD signal greater than 55 pC was recorded by the measurement device. 55 pC was selected to provide margin to the typical noise floor of the PD testing setup of approximately 48 pC. The voltage supply was disabled manually once a PD signal was detected. No minimum number of pulses was required. If an anomalous PDIV measurement was recorded for a given specimen, that specimen was retested. Specimen leads were often recleaned between measurements if an anomalous value was detected. Generally, the PDIV measurements reported in this paper were not rigorously made as the PD testing set up was learned and the authors gained experience with PDIV measurements. Gaining the knowledge base to establish a more rigorous PDIV measurement definition for future testing was a key result of this work. The lead cleanliness issues and the nonrigorous nature of the PDIV measurements should be noted when viewing the results in this paper.

Testing PDIV exposes the specimens to some amount of PD activity that could cause damage to the insulation and contribute to a lower measurement on a subsequent test. To gather initial understanding of whether this PDIV measurement method could affect subsequent tests, an unaged twisted pair was aged electrically in the testing setup significantly above the measured PDIV for 5 min increments. PDIV was remeasured after each electrical aging cycle. Table III shows the results of this aging. Approximately 92,700 V cycles above PDIV were applied to the specimen and no degradation in PDIV occurred. This result is likely due to the cycle count being significantly less than the electrical aging lifetime of the polyimide insulation. The thermal aging specimens reported in this paper have experienced less than 10,000 V cycles above PDIV throughout the test campaign. While this result gives some initial

TABLE III.—PDIV MEASUREMENTS FOR AN UNIMPREGNATED TWISTED PAIR AFTER ELECTRICAL AGING AT VOLTAGES ABOVE INITIAL PDIV

Electrical aging step	PDIV, Vrms
Initial	675
After 300 s at 1.2 kV	675
After 310 s at 1.5 kV	650
After 300 s at 1.8 kV	675
After 305 s at 2.1 kV	675
After 330 s at 2.4 kV	675

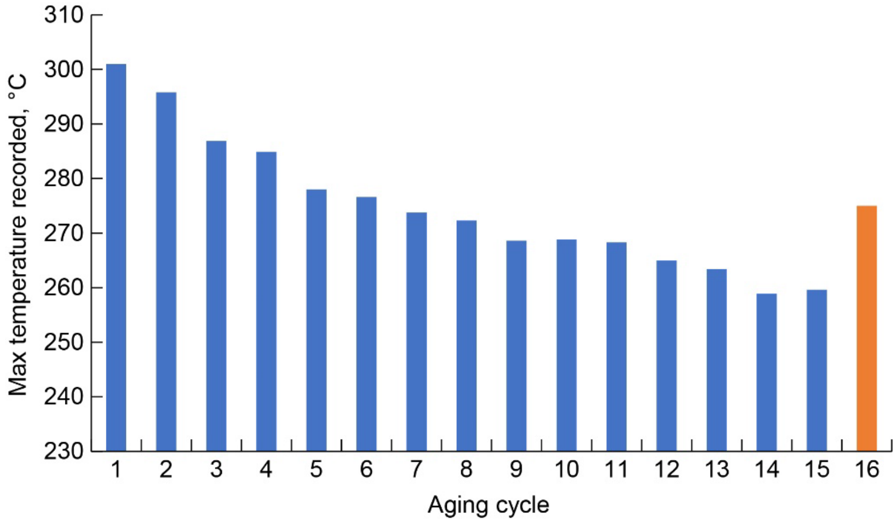

Figure 3.—Max temperature recorded for each constant temperature aging thermal cycle completed in the original furnace. Cycles 1 to 15 completed in original furnace. Cycle 16 completed in new furnace.

confidence that PDIV measurements do not affect the subsequent measurements significantly more testing is needed in future work to quantify the effect of the PDIV measurement cycles on the specimens after different amounts of aging.

2.3 Thermo-chemical Aging Setup

Thermal aging was carried out in an available furnace. Furnace temperature was set to 300 °C. A secondary thermal couple reading of the temperature in the furnace was used to monitor actual furnace temperature. The thermal couple was located in the furnace above the specimens and not in direct contact with the specimens. Unfortunately, the furnace available for this work was unable to accurately reproduce peak temperatures reached on each thermal aging cycle, and a practical decision was made to not manually compensate for this variation by increasing the furnace set point. Figure 3 shows the variation in peak temperature for each aging cycle. Appendix B contains all the temperature data recorded for every thermal aging cycle. Results in Section 3.0, translate the temperature data into equivalent time at 220 °C using the Arrhenius aging law as described in Appendix B. However due to the temperature variation of the furnace and the inconsistency of temperature data collection, the reported equivalent times at 220 °C should be taken as approximate.

A new furnace was obtained and made operational after the 15th thermal cycle. This new furnace was used for the 16th cycle due to the significant degradation in the old furnace's performance. A temperature of 275 °C was used for this last thermal cycle.

3.0 Results

3.1 Unimpregnated Pair Results

Figure 4 shows the PDIV values measured after each thermal cycle for the unimpregnated twisted pairs. PDIV is shown to stay relatively steady throughout the aging completed in this test campaign. The variation in PDIV increasing and decreasing throughout the data set is primarily attributed to the issues with the cleanliness of the wire leads as discusses in Section 2.0 and the PDIV criteria used in this

preliminary testing where a single PD signal greater than 55 pC was used to define PDIV. Overall, a downward trend in PDIV is observed as is shown in Figure 5 which shows the variation in min, max, and average PDIV for the dataset. Average PDIV is shown to only decay by roughly 75 Vrms. The aging completed however only accounts for ~3/8 of the thermal aging lifetime of the magnet wire insulation based on its thermal class (Refs. 4 and 5). Figure 6 shows a picture of the samples post aging. Visible color change of the wire insulation is apparent relative to the unaged samples in Figure 1.

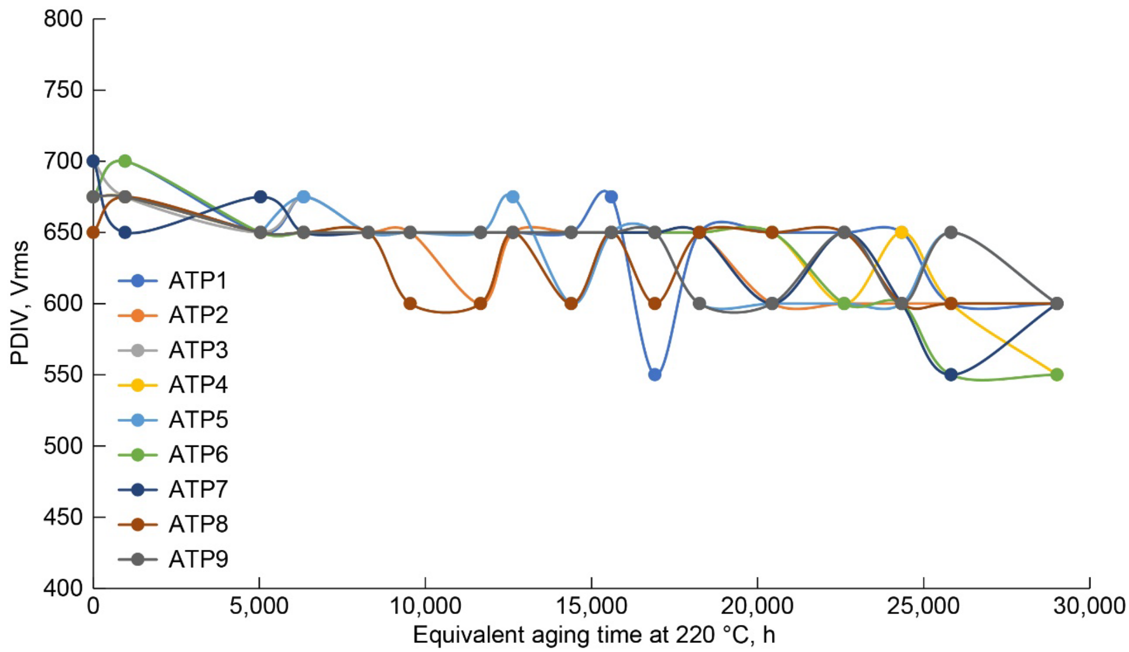

Figure 4.—PDIV measurement results for unimpregnated twisted pairs after each thermal cycle.

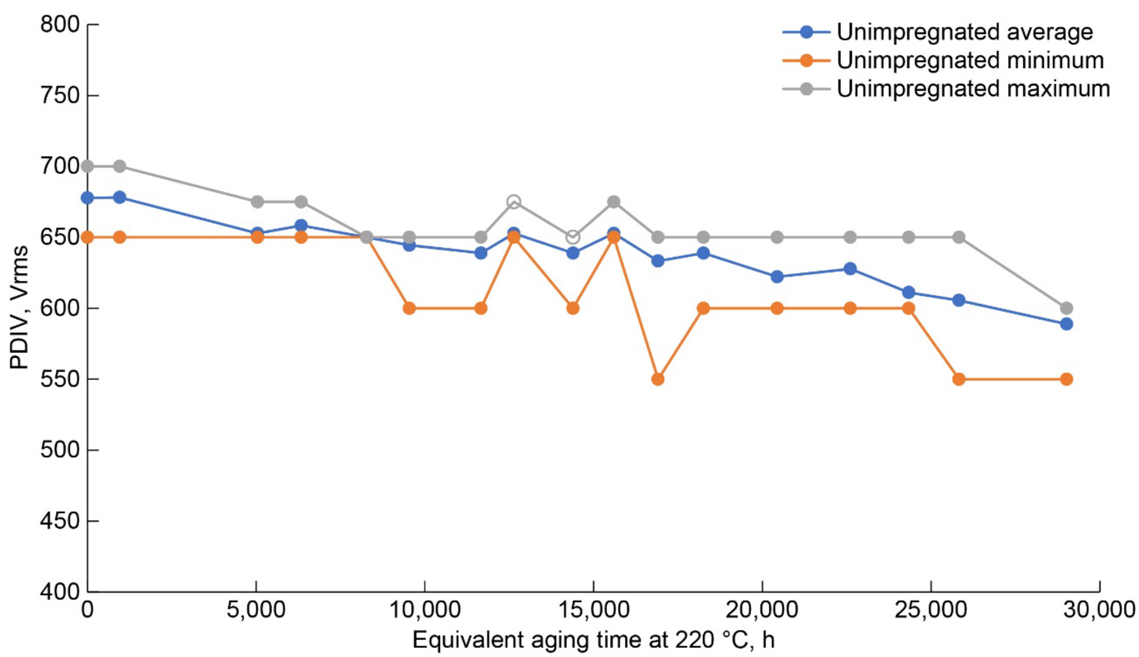

Figure 5.—Variation of minimum, maximum, and average PDIV measurement results for unimpregnated twisted pairs after each thermal cycle.

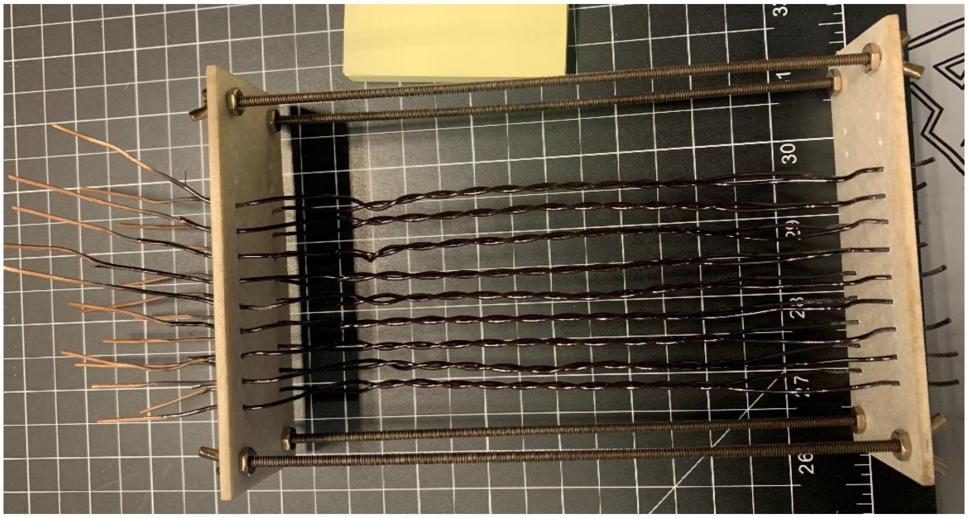

Figure 6.—Aged unimpregnated twisted pairs.

3.2 Epoxy #1 Potted Twisted Pairs

Figure 7 shows the PDIV variation for the specimens potted in epoxy #1. The average PDIV for the unimpregnated twisted pairs is also included as a reference. High initial PDIV measurements greater than 2 kV rms are recorded for the epoxy #1 potted specimens. This high initial PDIV either suggests the quality of the impregnation was good enough to eliminate PD at voltages below this value or reduced the PD magnitude to a value below the noise floor (Appendix A) of the PD measurement setup. Reduction of the noise floor in the PD testing set up is an ongoing effort to eliminate the possibility of lower magnitude PD being missed in future testing campaigns.

Significant PDIV degradation is observed for the epoxy #1 potted specimens in Figure 7 and all specimens eventually experience breakdown failures at the minimum voltage used in the test campaign. Breakdowns are noted by triangles in Figure 7. The earliest breakdown occurred at less than 10,000 h of equivalent aging at 220 °C. Figure 8 shows the specimens post aging. Visible color change, significant cracking of the epoxy, and curving along the length are observed. Given these specimens experienced dielectric breakdowns at less aging time than the unimpregnated twisted pairs despite being constructed from the same magnet wire and experiencing the same thermal cycles suggests that the epoxy caused significant mechanical stresses in the magnet wire insulation and damaged the polyimide insulation.

3.3 Epoxy #2 Coated and Potted Twisted Pairs

Figure 9 and Figure 10 show the results for the specimens coated and potted in epoxy #2 as well as the average value for the unimpregnated specimens. The potted twisted pairs are shown to have a lower initial PDIV value than epoxy #1 potted pairs, at around 900 V. Their PDIV however increased after the first round of thermal aging to greater than 1.2 kV but still lower than the initial PDIV of the epoxy #1 specimens. The lower initial values of PDIV for epoxy #2 potted specimens are attributed primarily to the authors inexperience with the potting process for epoxy #2.

The coated twisted pairs are shown to have a bit more variability in their initial PDIV measurement. This variability is attributed to the coating process used for these specimens where the thickness of the epoxy on each specimen was not well or uniformly controlled. Unlike the potted pairs, all but one of the coated specimens see no initial increase in PDIV after the first thermal cycle.

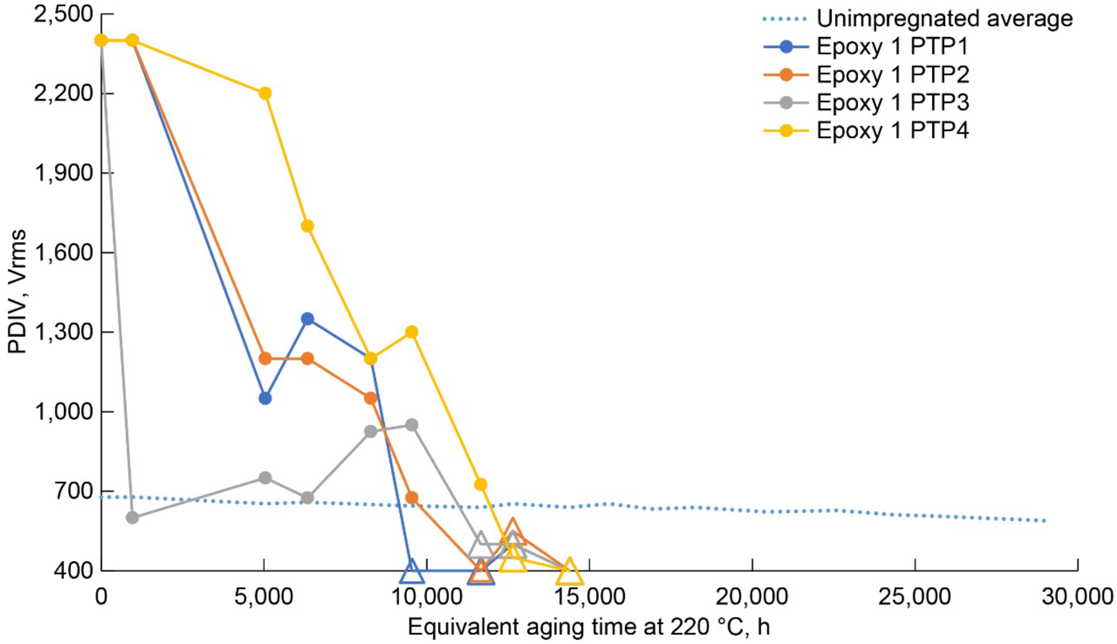

Figure 7.—PDIV measurements results for epoxy #1 potted twisted pairs after each thermal cycle. Data points marked with triangles are breakdowns of the insulation system.

Figure 8.—Specimens potted in epoxy #1 post aging.

Both potted and coated twisted pairs are shown to have steady decay in their PDIV values after the initial variation for the potted pairs. Both sets of PDIV values eventually drop to under 700 V, which is comparable to the PDIV values for the unimpregnated twisted pairs. At under 700 V the PDIV benefit of the epoxy is essentially eliminated. For the coated pairs the average drops below 700 V after ~7000 equivalent hours at 220 °C. The potted twisted pairs took about twice as long for their average PDIV to drop below 700 V. All specimens took more than twice the epoxy’s estimated rated life of 1250 h at 220 °C based on its manufacture listed thermal class for their PDIV to decay under 700 Vrms.

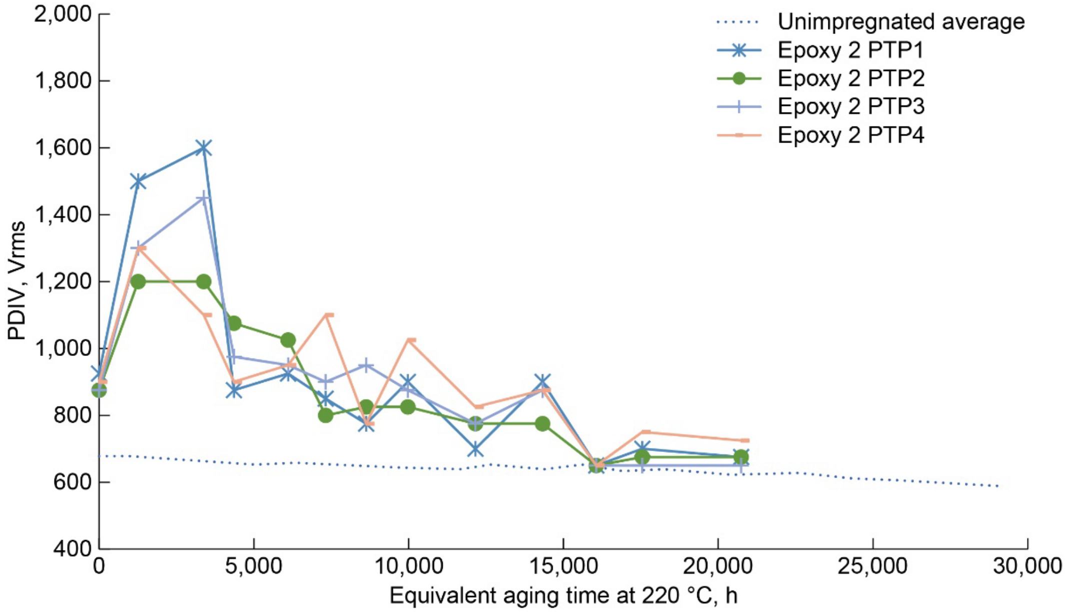

Figure 9.—PDIV measurements results for epoxy #2 potted twisted pairs after each thermal cycle.

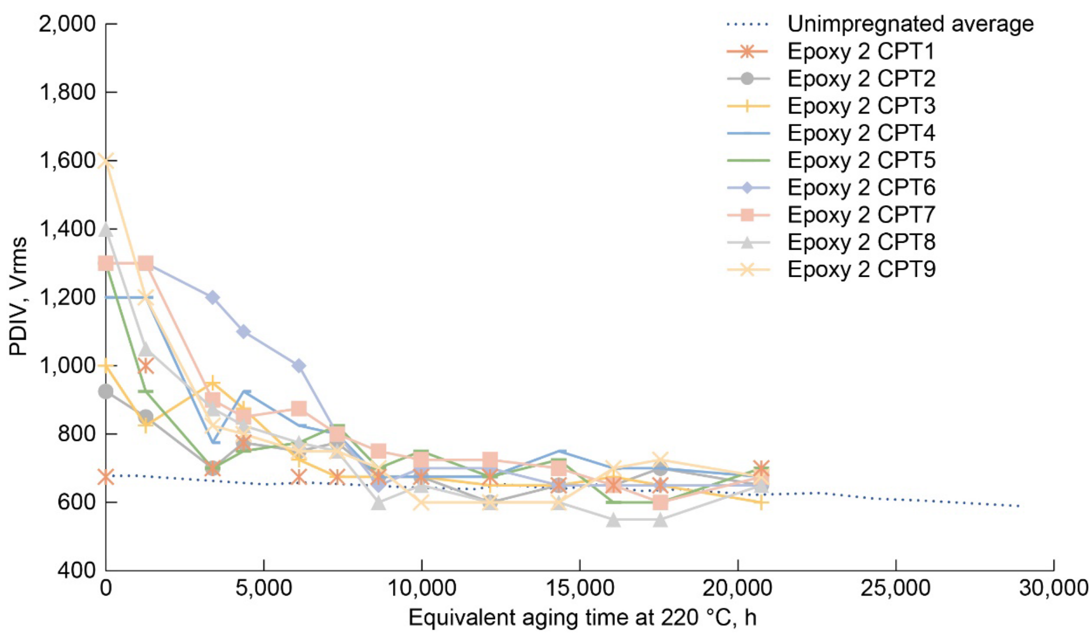

Figure 10.—PDIV measurements results for epoxy #2 coated twisted pairs after each thermal cycle.

Figure 11 and Figure 12 show the specimens after aging. Color change is visible in both specimen types and visible cracking is present in the potted twisted pairs. Relative to epoxy #1 no break down failures occurred in the specimens potted in epoxy #2, however. This result along with how the PDIV values only decayed to the range of unimpregnated pairs suggests that the specimens potted in epoxy #2 did not experience high enough thermal mechanical stress to damage the polyimide insulation.

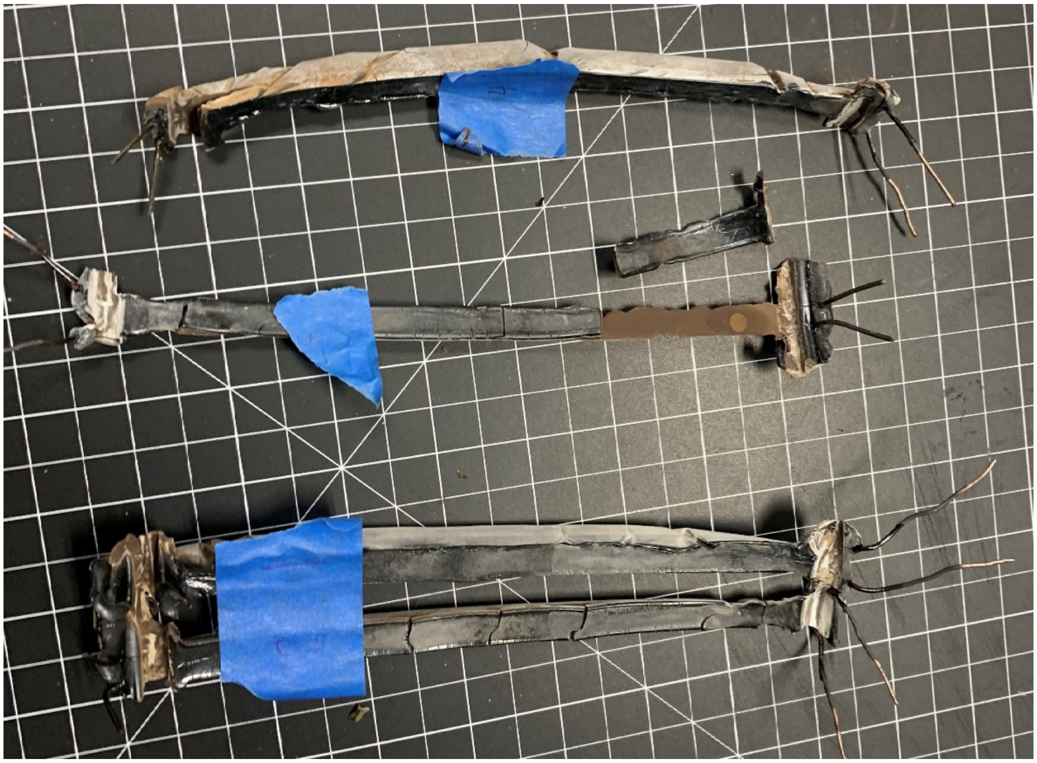

Figure 11.—Epoxy #2 potted twisted pairs after aging.

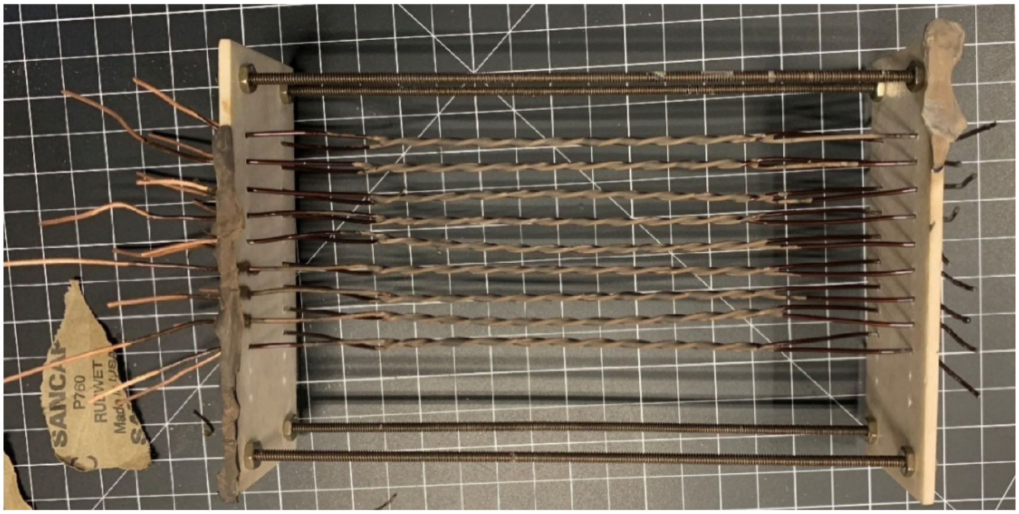

Figure 12.—Epoxy #2 coated twisted pairs after aging.

3.4 Min and Average PDIV Comparison

The average and minimum PDIV value variation with equivalent time at 220 °C are plotted in Figure 13 and Figure 14, respectively for all specimen types. The degradation of the PDIV of the potted twisted pairs to the PDIV levels of the unimpregnated twisted pairs is shown. These preliminary results suggest that while both epoxies enable an initial increase in PDIV over unimpregnated pairs, a motor would have to be designed for a shorter lifetime or lower thermal stress to take advantage of the PDIV increase, because PDIV for the specimens drops to the range of the unimpregnated pairs fairly quickly. Epoxy #1 in particular is shown to not be able to maintain its higher PDIV with thermal age.

The high aging temperatures used in this preliminary testing may have affected the results for both epoxies. High temperatures were intentionally selected for this preliminary round of testing to guarantee the degradation of the specimens occurred in a reasonable amount of time. Based on these results both epoxies will be aged at lower temperatures in subsequent aging experiments.

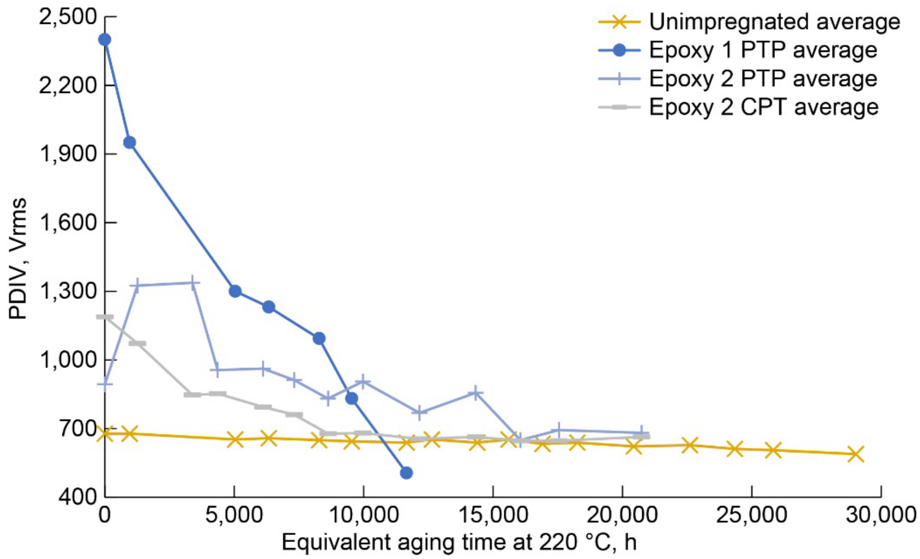

Figure 13.—Average PDIV variation with thermal age for all specimen sets.

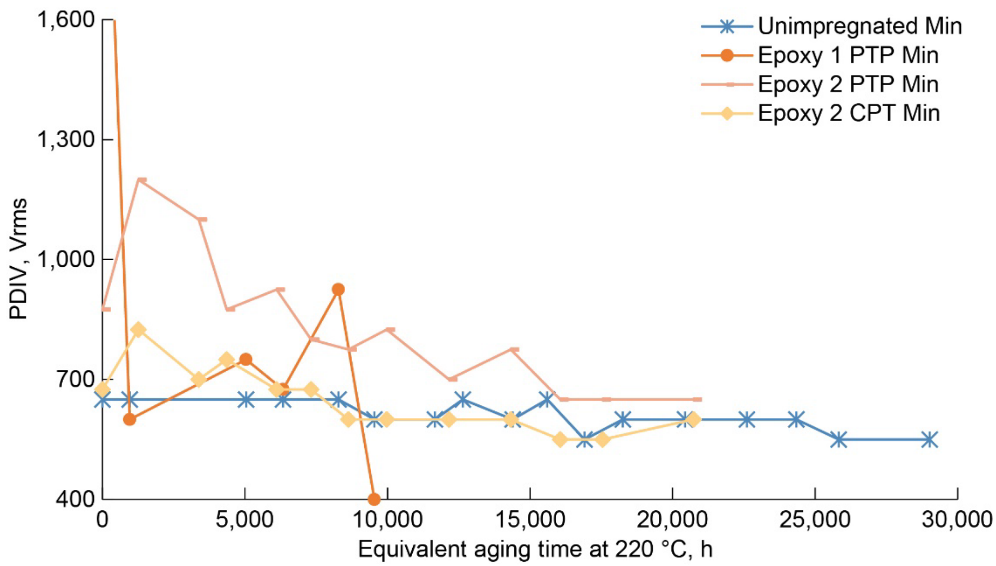

Figure 14.—Minimum PDIV variation with thermal age for all specimens sets.

4.0 Conclusion

This paper presented preliminary results for constant temperature thermal aging of magnet wire twisted pairs. Impregnated and nonimpregnated MW-16C class magnet wire twisted pairs PDIV was tracked with thermal age. Two different epoxies were used to impregnate twisted pairs. The impregnated pairs PDIV was shown to decay to that of the unimpregnated pairs as they were aged. Twisted pairs potted in the first of the two epoxies failed the insulation such that breakdown occurred at the lowest test voltage used in this campaign. Results of this preliminary work will be used to inform future winding aging experiments.

Future work will focus on

1. Refining the PDIV measurement process to reduce noise levels and improve the consistency of the measurements.
2. Further PDIV testing of twisted pairs with better PDIV measurements and more consistent furnace temperatures.
3. Expansion of PDIV measurement to be able to test specimens with relevant inverter frequencies and waveforms.
4. Thermo-mechanical aging testing of motorrettes and twisted pairs

Appendix A.—Noise and Calibration Information for Each Test

Date	Noise voltage source inactive, pC	Noise voltage source active, pC	Calibration, pC	Ref specimen PDIV, Vrms
6/01/2023	1.45	45.60	20.00	650.00
6/28/2023	0.66	47.90	20.00	650.00
7/3/2023	0.52	48.50	20.00	650.00
7/7/2023	0.65	48.2	20.00	650.00
7/12/2023	1.41	48.20	20.00	650.00
7/14/2023	0.45	48.10	20.00	650.00
7/20/2023	0.41	47.50	20.00	675.00
7/31/2023	~	47.50	20.00	675.00
8/4/2023	~	48.00	20.00	650.00
8/9/2023	0.80	~	20.00	650.00
8/15/2023	0.80	~	20.00	675.00
8/18/2023	~	47.10	20.00	675.00
8/24/2023	0.50	47.80	20.00	675.00
8/30/2023	0.53	47.50	20.00	675.00
9/7/2023	0.75	47.00	20.00	650.00
9/14/2023	1.05	47.00	20.00	650.00
10/4/2023	~	25.00	20.00	675.00

Appendix B.—Furnace Data and Thermal Age Calculations

Figure 15 shows all data collected for furnace temperatures throughout the testing campaign. Figure 16 shows a zoomed in view of the heat up time for every cycle. Figure 17 shows all the data collected for the furnace cooling down post shut down.

Equivalent time at 220 °C was estimated by Arrhenius law so that life consumed for a given cycle is

$$t_{220} = \int_0^{\tau} 2.38\mathrm{E}(-7) * \mathrm{e}^{(0.0693 * T)}\, dt$$

where t_{220} is time at 220 °C, τ is the total time of a thermal cycle, T is temperature, and t is time Based on the data in Figure Y and Z, cool down and warm up was assumed to be roughly uniform for each thermal cycle. Warm up is assumed to contribute 73 h of aging at 220 °C and cooldown is assumed to contribute 14 h of aging at 220 °C in the data reported in Section 3.0.

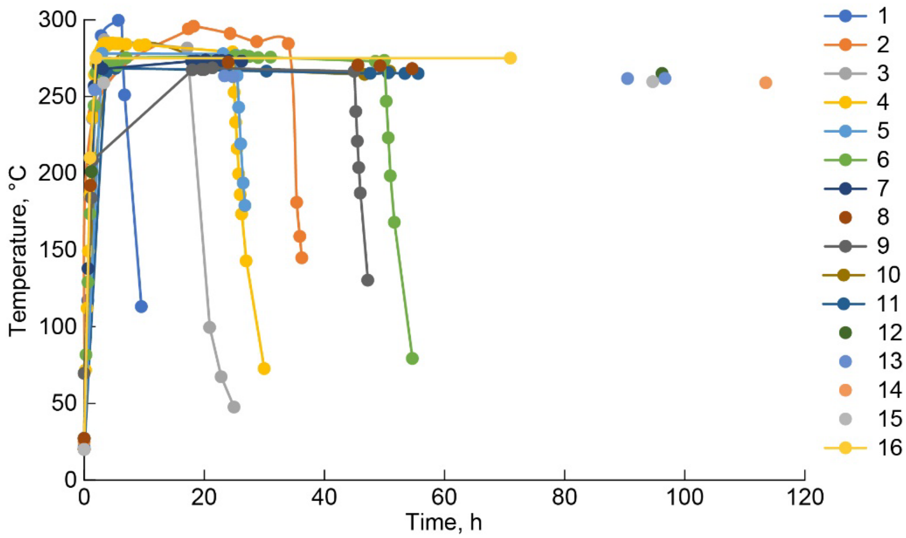

Figure 15.—Thermal couple data points collected from all thermal aging cycles. Note that different times at temperature were used on different cycles.

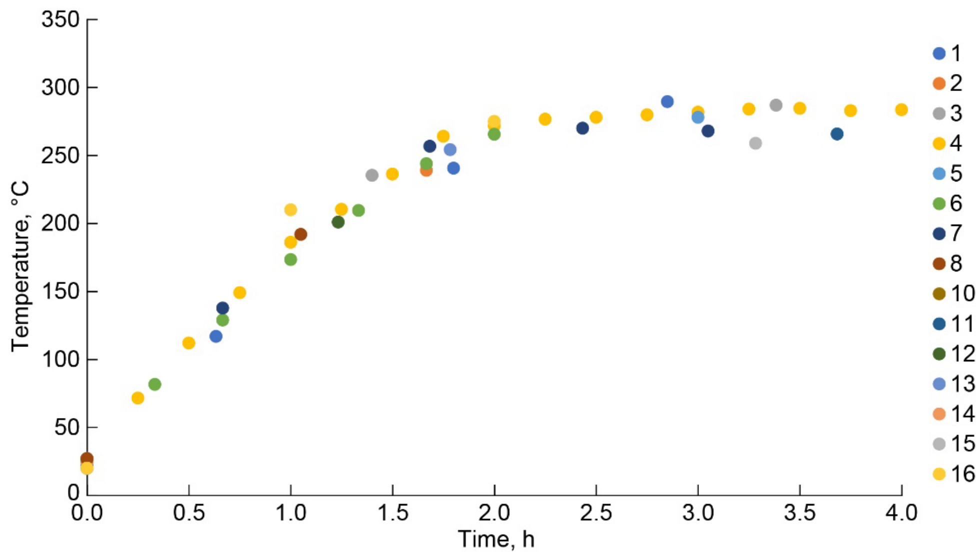

Figure 16.—Heat up data points collected for thermal cycles.

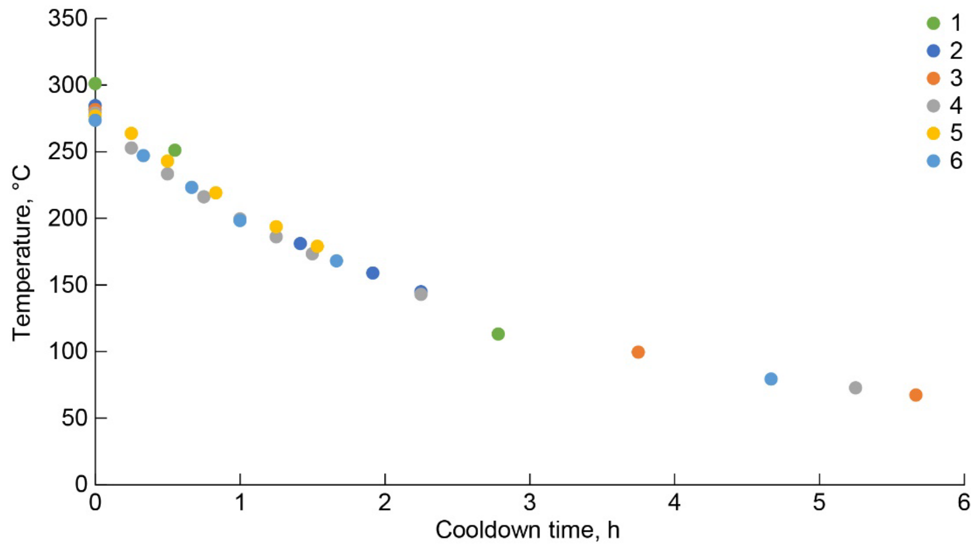

Figure 17.—Cooldown temperature data points collected for every thermal cycle.

References

1. P.R. Darmstadt, R. Catanese, A. Beiderman, F. Dones, E. Chen, M.P. Mistry, M. Beckman, and R. Preator, “Hazards Analysis and Failure Modes and Effects Criticality Analysis (FMECA) of Four Concept Vehicle Propulsion Systems,” NASA, 2019.
2. T. Tallerico, T. Krantz, M. Valco, and J. Salem, “Urban Air Mobility Electric Motor Winding Insulation Reliability: Challenges in the Design and Qualification of High Reliability Electric Motors and NASA’s Research Plan,” NASA, Cleveland, 2022.
3. G.C. Stone, Culbert, Ian, E.A. Boulter, and H. Dhirani, Electrical Insulation for Rotating Machines: Design, Evaluation, Aging, Testing, and Repair, Second ed., I. Press, Ed., Hoboken, NJ: John Wiley & Sons, Inc., 2014.
4. National Electrical Manufacturers Association, “NEMA MW 1000-2003,” National Electrical Manufacturers Association, Rosslyn, VA, 2003.
5. ASTM, ASTM D2307-2013 Standard Test Method for Thermal Endurance of Film-Insulated Round Magnet Wire, ASTM, 2013.
6. IEC, “IEC 60034-18-41: Partial discharge free electrical insulation systems (Type I) used in rotating electrical machines fed from voltage converters – Qualification and quality control tests,” The International Electrotechnical Commission, Geneva, 2019.
7. A. Rumi, A. Cavallini, and J. Marinelli, “The Impact of Impregnating Resins in Ensuring the Reliability of Inverter-Fed Machines,” in *2020 International Symposium on Electrical Insulating Materials*, Tokyo, Japan, 2020.
8. A. Rumi, J.G. Marinelli, and A. Cavallini, “Converter Stress Impact on Thermally Aged Resin for Low-Voltage Machines,” in *IEEE Conference on Electrical Insulation and Dielectric Phenomena*, Vancouver Canade, 2021.
9. F. Loubeau, P. Rain, A. Durieux, and F. Le Strat, “Partial discharge behavior of motorettes under different aging conditions,” in *2018 IEEE 2nd International Conference on Dielectrics (ICD)*, Budapest, Hungary, 2018.
10. Cotronics, “DURAPOT™ EPOXIES High Performance Casting, Embedding and Encapsulating Compounds For Electronic Applications,” [Online]. Available: https://www.cotronics.com/. [Accessed 2023].

11. G. Szpak, A. Smith, J.T. Thompson, A. Woodworth, and R. Jansen, “High Efficiency Megawatt Motor Thermal Stator Preliminary Design,” in *AIAA/IEEE Electrified Aircraft Technologies Symposium*, New Orleans, 2020.
12. A.A. Woodworth, R. Jansen, K. Duffy, P. Nazhipour, and E. Shin, “Creating a Multifunctional Composite Stator Slot Material System to Enable High Power Density Electric Machines for Electrified Aircraft Applications,” in *AIAA/IEEE Electric Aircraft Technologies Symposium*, Cincinnati, 2018.
13. A. Woodworth, A. Smith, R. Jansen, and G. Szpak, “Select Variables Affecting Thermal System Design of a Liquid Cooled Stator,” in *AIAA/IEEE Electric Aircraft Technologies Symposium*, Virtual, 2020.
14. A.A. Woodworth, A. Smith, W. Sixel, R. Edwards, R. Jansen, S. McCormick, M. Robbie, G. Szpak, P. Naghipour, and E.-S. Shin, “Thermal Analysis of Potted Litz Wire for High-Power-Density Aerospace Electric Machines,” in *AIAA Propulsion and Energy Forum*, Indianapolis, 2019.
15. A.J. Samarakoon, T. Tallerico, B. Wolhaupter, T. Balachandran, and K. Haran, “Partial Discharge Investigation of Electric Machine Winding due to Thermo-Mechanical Stresses for Electric Aircraft Propulsion,” in *International Electric Machines and Drives Conference (IEMDC)*, San Francisco, 2023.
16. Parker LORD Engineering Materials Group, “CoolTherm® EP-2000 Thermally Conductive,” 2021. [Online]. Available: www.lord.com. [Accessed 2023].
17. International Electrotechnical Commission, “IEC 60270: High Voltage test techniques - Partial discharge measurements,” International Electrotechnical Commission, 2015.